The Best Shape for a Crossdock

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Abstract

Crossdocks supporting the retail and less-than-truckload (LTL) freight industries vary greatly in shape. We have seen ones in the shape of an I, L, T, and H. Which is best? We show how the answer depends on the number of doors, the ratio of receiving to shipping doors, and the distribution of material flows inside. Our results suggest that many current crossdocks suffer from bad design that increases consequent labor costs.

1 Crossdocking

Of the four major functions of warehousing — receiving, storage, order picking, and shipping — the middle two are typically the most costly: storage because of inventory holding costs, and order picking because it is labor-intensive. Crossdocking is a logistics technique that eliminates the storage and order picking functions of a warehouse while still allowing it to serve its receiving and shipping functions. The idea is to transfer shipments directly from incoming to outgoing trailers without storage in between. Shipments typically spend less than 24 hours in a crossdock, sometimes less than an hour.

Crossdocking is an important logistics strategy for many firms in the retail, grocery, and other distribution industries. Stalk et al. (1992) report that Wal-Mart considers crossdocking a core capability, and that the practice was a major reason it surpassed K-Mart in total sales in the 1980s. Because Wal-Mart was able to reduce total system inventory with crossdocking, it could offer the "everyday low price" for which it is now famous. In the grocery industry, crossdocking has allowed firms to reduce inventories and transportation costs in the midst of fierce price competition. Crossdocking is also a mainstay practice of less-than-truckload (LTL) trucking firms, which seek to consolidate shipments to achieve transportation economies.

E-commerce, B2B marketplaces and improved supply chain coördination have drastically lowered transaction costs, which until now have been the traditional justification for large order quantities and higher inventory levels. Lower transaction costs, in turn, have led to smaller shipment sizes and a need to consolidate to regain transportation economies.

For example, Home Depot operates a crossdock in Philadelphia that serves more than 100 stores in the Northeast. Home Depot's culture allows store managers a great deal of autonomy with regard to product selection, inventory levels, and so on. In the past, each store ordered from vendors separately, and orders were sent in LTL shipments directly to the stores. Home Depot now uses crossdocking to reduce costs from the vendor by consolidating orders among its stores and ordering in truckload quantities from vendors.

Here is how the new system works: Each of the 100+ stores orders from each vendor on a specific day of the week. The vendor consolidates all orders and sends truckloads of product to the crossdock in Philadephia. There, workers transfer products to trailers bound for individual stores (or 2 stores on a few multi-stop routes), so that outgoing trailers contain products for very few stores from many vendors. Transportation costs are lower because shipments into and out of the crossdock are in truckload quantities.

Crossdocking is economical as long as handling costs do not overwhelm transportation and inventory savings, and it is handling costs that we address. Material handling in a crossdock is labor intensive for at least three reasons. First, freight is often oddly shaped (particularly in the LTL industry), so automation is difficult. Second, even in retail crossdocking where freight is more uniform, automated material handling systems are not as flexible as a labor force with respect to costs and throughput. Flexibility is especially important for retail firms because they often suffer severe seasonalities. Third, automation requires a huge fixed cost, which many firms are reluctant to make in a dynamic business logistics environment.

Labor costs in a crossdock are due to a number of operational and design characteristics, including the assignment of trailers to doors (the layout), the mix of freight flowing through the facility, available material handling systems, how arriving trailers are scheduled into doors, and the shape of the facility. Layout and material handling systems for crossdocking have been addressed by Peck (1983), Tsui and Chang (1990, 1992), and Bartholdi and Gue (2000). Gue (1999) reports on the effects of scheduling trailers into doors on the layout of a crossdock. In this paper, we address the shape of crossdocks.

Some work has been reported on the related problem of best shape for an airport terminal. Results in airport design research are driven by the two categories of passengers: arriving-departing passengers, who travel between a gate and the entry point of the terminal, and transferring passengers, who travel from gate to gate. de Neufville and Rusconi-Clerici (1978) argue that pier-finger designs, in which a terminal has two or more piers extending from it, are appropriate when the percentage of transferring passengers exceeds about 30%.

Robusté (1991) and Robusté and Daganzo (1991) describe geometric relationships for airport terminals. They show that optimal shapes with respect to walking distance depend on the proportion of each type of customer the airport serves. Robusté and Daganzo (1991) show that for large terminals with transferring passengers only (the case most analogous to a crossdock), the best design is a closed loop with equally long radial piers extending from its exterior, which the authors call a "sun" design. For terminals with a mix of arriving-departing and transferring passengers, piers farther from the terminal should be shorter to reduce average gate-to-terminal travel. Bandara and Wirasinghe (1992) point out that, by design, transferring passengers tend to connect to another flight of the same airline and that is likely to be at a gate in the same pier as arrival, or at least nearby.

Crossdock design differs from airport design in a number of ways: First, all freight in a crossdock is "hub freight"; that is, freight does not begin or end its travel at a crossdock the same way that a passenger does at an airport.

Second, because they minimize total distance between all pairs of gates (for transferring passengers) or gates and the terminal (for arriving and departing passengers), airport models implicitly assume equal passenger activity at all gates. This is not a bad assumption for airports because after passengers depart an aircraft, other passengers board it at the same gate, so activity tends to be quite distributed. But this is a poor assumption for crossdocks because doors are permanently assigned as receiving or shipping doors, and the material flows to particular shipping doors vary widely. Doors in a crossdock do not change designations for several reasons:

- To minimize double handling due to staging freight, crossdocks typically have a shipping door available for every destination all the time, obviating the need to convert a recently emptied inbound trailer to an outbound trailer.

- Transported entities in an airport (people) are autonomous, and, on the whole, are capable of not walking onto the wrong plane; but in a crossdock freight can easily be loaded into the wrong trailer if doors change destinations and function. (Bar code scanning systems are available to prevent such misloads but are costly and rarely used.)

- Workers tend to be more efficient when they have committed door locations to memory.

The result of these static designations is that doors experience the same unbalanced flows as their corresponding destinations. It is quite typical in our experience for these flow rates to differ by a factor of 2–10.

Third, where orthogonal segments of a terminal join, doors (cf. gates) are unusable because vehicles would overlap otherwise. This effect is much more significant for crossdocks than for airports: One 48-foot trailer can overlap four door positions and so there is greater potential interference among doors near a corner.

A fourth way in which crossdock design differs from airport design is that inefficiencies in an airport are inflicted upon passengers, not upon the operating authority. In a crossdock, inefficiencies directly increase operating costs.

Finally, it is worth remarking that the crossdocking facilities we consider face a different set of problems than package-handling terminals such as those of UPS or FedEx. Package-handling terminals restrict their business to uniform sizes of package, which enables extensive use of conveyors. Consequently, in package-handling terminals, labor costs are not a direct function of travel between doors.

2 Crossdock design

Because crossdocking is a relatively new practice in the retail industries, the LTL trucking industry still operates most of the crossdocks in the United States. Code (2000) reports that there are more than 9,000 crossdocks in the United States and Canada.

Most crossdocks are long, narrow rectangles (an I-shape) but we have also seen crossdocks shaped like an L (Yellow Freight), T (American Freightways in Atlanta), H (Central Freight in Dallas), and E (outside Chicago). How to account for this variety? Is one shape best?

Firms acquire their crossdocks in a variety of ways and do not always have the luxury of building a new one. Consequently they may be heir to someone else's bad design if they lease or convert an existing facility. Even if they design new facilities, the lead designers are likely to be civil engineers or commercial real estate firms, which are experts in topics like ingress and egress from the facility, parking lot construction, and building codes; but they are not likely to pay close attention to internal performance measures like travel cost or congestion.

Sometimes the dock shape is determined by simple constraints such as the size and shape of the lot on which it will stand. Commercial real estate in the most desireable locations is often very expensive or hard to find, forcing a distribution firm to trade off location for lot size and shape. Engineers at Yellow Freight report that some of their L- and T-shape crossdocks were constructed to accommodate lot restrictions (Hammeke, 2000). Other issues complicate the placement of a crossdock on a lot, such as parking requirements, the turning radius of trucks, and the need for office or maintenance buildings.

All these issues force compromises in the design of a crossdock. However, we ignore these particular complications to focus here on a single issue, shape, and how it affects crossdock performance.

2.1 Number of doors

One of the first design decisions is how many doors a crossdock should have. Crossdocks have two types of doors: *receiving* doors (also called strip or breakout doors) and *shipping* (or load) doors. The number of shipping doors is relatively easy to determine because the firm usually knows how many destinations the crossdock must serve. If each destination requires one door, then the number of shipping doors equals the number of destinations. A high-flow destination may require more than one door in order to provide sufficient "bandwidth" to the destination. (The extreme in our experience is a crossdock in Dallas that allocates 10 doors to Houston to accommodate the 25–30 trailers of freight bound there every night.)

There are more issues involved in determining the number of receiving doors. In many retail crossdocks one side of the facility is devoted to receiving doors and the opposite side to shipping doors and their numbers are equal. This configuration supports orderly staging of pallets and value-added processing, such as packaging, pricing or labelling. For LTL crossdocks, which generally do no value-added processing, Little's law provides a simple way to estimate the number of receiving doors by multiplying the required throughput of trailers by the average time to unload a trailer. At Yellow Freight, the largest LTL carrier in the world, the average hub crossdock has about 180 doors (satellite crossdocks are smaller) and slightly more than 38% of them are receiving doors. This percentage is slightly smaller for smaller docks and grows to about 45% for their largest docks, which have as many as 300 doors (Trussell, 2001). This is consistent with our experience and suggests that we span practice by considering crossdocks of up to 400 doors, with a fraction of receiving doors that ranges from 0.05 to 0.50.

Finally, we observe that all crossdocks in our experience place all doors at equal intervals (generally about a 12-foot offset).

3 The effect of dock shape on operations

3.1 The basic design

Most smaller crossdocks are I-shaped, because this design offers the chance to move freight directly across the dock from receiving door to shipping door. Short, across-the-dock travel is important because crossdocking operations are labor-intensive and most of the variable cost of labor is devoted to travel between doors.

Distribution managers generally prefer narrow docks to reduce labor cost. Their intuition seems to be based on imagined freight flows in which product is conveyed directly across the dock, which is true for approximately half of all freight flows (assuming an approximately balanced dock). The following observation confirms their intuition.

Observation 1 *For the same number of doors a narrower dock realizes a smaller average distance between doors.*

See Appendix A for a proof.

Narrower docks are more efficient, but it is necessary to leave room to stage freight, especially in front of shipping doors. Freight must be staged for several reasons:

- To build tightly-packed loads,
- To load in reverse order of delivery if there will be multiple stops,
- To place fragile freight on top, and
- To build "nose loads" (put that freight at the front of the trailer that does not need to be sorted at subsequent stops).

If there is too little staging area the dock becomes congested and throughput decreases. This is especially problematic when a company is growing or is at a seasonal sales peak and throughput must rise. Consequently it is standard practice to make the dock 1–2 trailer lengths wide to provide space to dock freight. (Retail crossdocks are typically wider to allow for value-added processing.) The exact width depends on the estimated need to dock freight, which in turn depends on the freight mix, number of stops per trailer, amount of palletized freight, and so on. Consequently the appropriate dock width is, to some extent, particular to the operation. In practice most crossdocks are 5–10 doors wide and so we shall assume that this dimension has been determined, is small and is fixed throughout the remainder of the discussion.

Because the width is small and fixed, the efficiency of an I-shape is determined by its longer dimension:

Definition 1 *The* diameter *of a crossdock is the largest distance between any pair of doors.*

The problem with the I-shaped design is that it loses efficiency as the number of doors increases, because the diameter increases quickly, and some freight will have to travel this extreme distance. For example, for a dock of 250 doors, the distance between doors at opposite ends of an I-shaped crossdock is almost a quarter mile. We measure this tendency as follows: For I-shaped docks, adding four additional doors (two to each end) increases the diameter of the dock by two door offsets, so the rate of growth of the diameter is $4/2 = 2$ doors per door offset. We refer to this ratio as the *centrality* of the dock. A large value of centrality is good because the maximum travel distance does not grow too quickly as the number of doors increases.

A second problem is that the traffic past the middle of the dock increases with the square of the number of doors and so congestion of forklift traffic can quickly become a problem at the center of the dock (Bartholdi and Gue, 2000).

It is to avoid such deterioration in efficiency that other designs, such as L, T, H, or E, have been considered. These designs differ from the standard I-shape in one important way: They have additional corners, which exact their own particular costs.

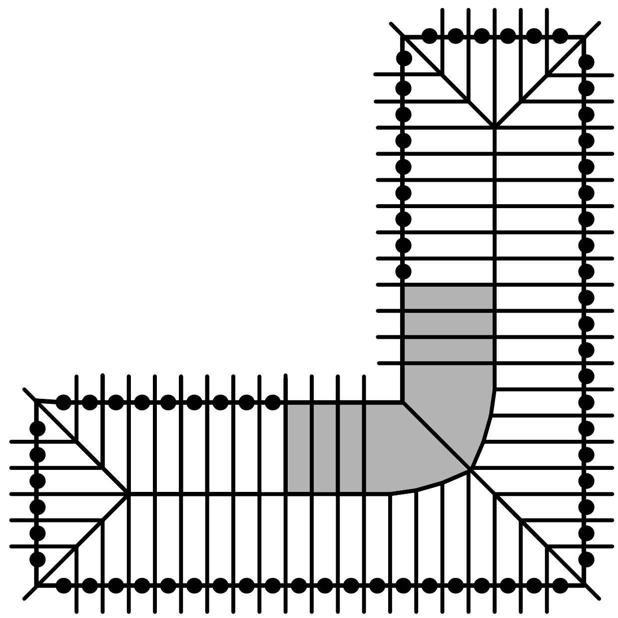


Figure 1: A Voronoi diagram partitioning available floor space among doors for staging freight. An inside corner forfeits usable door positions, which means that the dock must be larger for a given number of doors. Furthermore, the extra floor space in front of the unusable doors is not convenient to doors that may need it.

3.2 The costs of corners

There are two kinds of corners, inside corners and outside corners, and each incurs its own kind of cost.

On an inside corner, door positions are rendered unusable due to overlapping access paths as shown in Figure 1. For standard 48-foot trailers parked at a dock with 12-foot door offsets, at least $48/12 = 4$ doors on each side of an interior angle are unusable; and in practice this number is generally more conservative, 4–6. This means the dock must be 8–12 door positions larger to realize the same number of usable doors, which means the total travel time within the dock will be larger.

There is also an opportunity cost to an inside corner: In L, T, H, X, and E-shapes the inside corners tend to be near the center of the dock, which means that the door positions that are rendered unusable are among the most conveniently located.

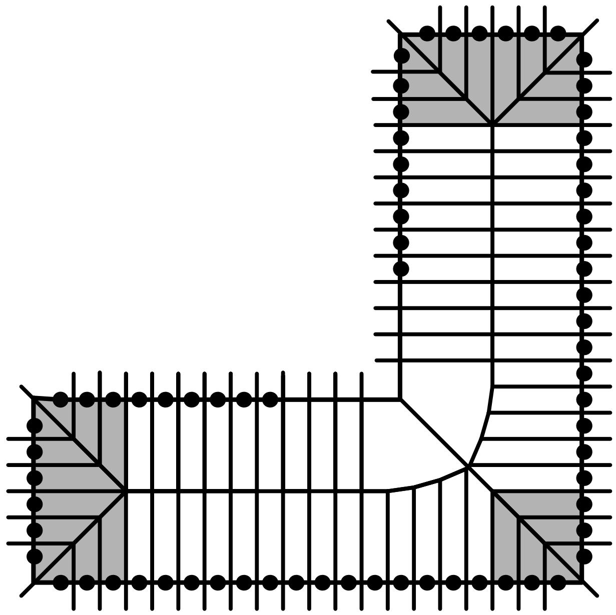


Figure 2: A Voronoi diagram partitioning available floor space among doors for staging freight. The six doors on each outside corner have only three shares of floor space and therefore are more susceptible to congestion.

An outside corner exacts a different cost: Doors on the outside of a corner have less floor space available to dock freight and therefore are more susceptible to congestion. This may be seen in Figure 2, where a Voronoi diagram partitions the dock into (mostly) uniform shares of floor space. This is a natural way of assigning floor space to doors for the docking of freight. As suggested by Figure 2, it is easy to confirm the following.

Observation 2 *If a dock is w door positions wide then each outside corner loses $w/2$ doors' worth of floor space.*

We can conclude that for a typical crossdock (six doors wide, hosting 48-foot trailers, with doors at 12-foot offsets) each outside corner forfeits 3 shares of floor space and each inside corner forfeits 8 door positions.

Table 1 summarizes the key characteristics of various dock shapes. This table makes it clear why, for example, an L-dock is strictly inferior, from an operational point of view, to an I-dock: The L-dock has centrality 2, like the I. This means the inside corner, which

	#-corners		
Shape	*Inside*	*Outside*	Centrality
I	0	4	2
L	1	5	2
T	2	6	$6/2 = 3$
X	4	8	$8/2 = 4$
H	4	8	$8/2 = 4$

Table 1: Characteristics of several dock shapes

adds at least 8 door positions, increases the diameter by at least $8/2 = 4$ door offsets. In addition, the L-dock incurs the cost of the additional outside corner, which forfeits 3 door-shares of dock space. Thus the L-dock is more costly than the I-dock and does not confer any compensatory benefit.

The T-dock has two inside corners, which add $(2)(8) = 16$ door positions to increase the diameter by $\lceil 16/3 \rceil = 6$; and there are two additional outside corners. But the greater measure of centrality means that the dock can add more doors before the diameter becomes excessive. The additional corners are a sort of fixed cost to enable the greater centrality, which begins to pay off for larger docks. This effect is greater still for the H and X-docks: The additional corners represent a still greater fixed cost to achieve a still greater centrality.

The question is: Does the benefit of centrality justify the cost of additional corners? To answer this question we must measure the convenience of door location.

3.3 The convenience of a door location

We measure the distances that freight travels across the dock as if all travel is rectilinear. This is appropriate because travel is approximately rectilinear to avoid docked freight.

Generally speaking, some doors are more convenient than others and these are the doors at the center of the dock. They are more convenient because they are closer to more doors and so provide more opportunities to move freight quickly. Figure 3 demonstrates the difference between the single best and single worst doors on a dock. The best door is no closer to its

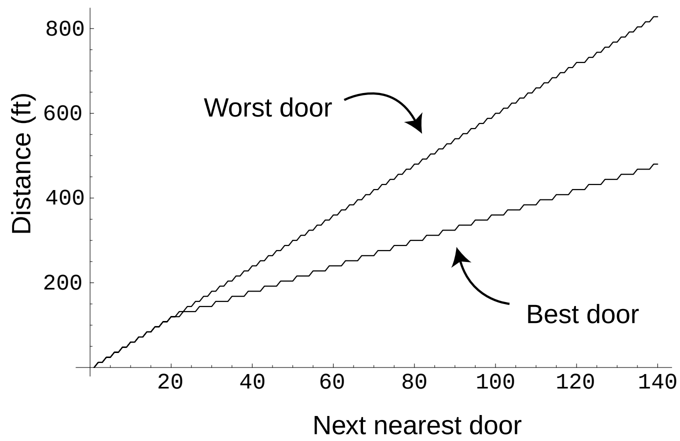


Figure 3: Distances to other doors sorted from nearest to most distant for the best door and worst door on a 140-door dock.

nearest door (each door has equally distant next-door neighbors), but it is much closer to its most distant doors than is the worst door to its most distant doors, making it a better choice for high levels of flow.

The curves in Figure 3 are identical through the 20^{th} doors because they represent the distances to adjacent doors on either side of the best- and worst-doors, and the sample dock is 10-doors wide. However, the 21^{st} closest door to the best door is *across* the dock, rather than farther down the side, as for the worst door. After this point, distances increase at half the rate for the best door because the next closest door is one door-width farther away for every four doors (one on each side of the door on the same side of the dock, and one on each side across the dock), rather than every two doors, as for the worst door.

For crossdocks with a smaller length to width ratio, the curves would not diverge as dramatically because the point of separation occurs further to the right. This implies that the difference between best and worst doors is not as great for smaller docks, which typically have a smaller length to width ratio, and explains why careful placement of trailers into doors is more important for large crossdocks.

It is also worth remarking that the best doors in a crossdock are not only closer to other doors in aggregate, but they are also closer to other high-quality doors.

4 Evaluating shapes

To get a more accurate idea of the effects of dock shape we must examine the efficiency of the dock in moving expected freight flows. We study dock shapes under two models of freight flows:

Uniform freight flows mean that every inbound trailer sends equal amounts of freight to every outbound trailer. Of course this is an extreme case and so will help test the robustness of our conclusions. Uniform flows magnify the weaknesses of any dock because it is hard to avoid regions of bad design by judicious assignment of trailers to doors.

Exponential freight flows follow an "ABC" rule in which most of the freight of each inbound trailer is bound for the same few outbound trailers. This model is suggested by Figure 4, which shows the relative amounts of product moving out of stores of The Home Depot in the northeastern U.S. In this model, we assume that when a trailer arrives from a vendor at the crossdock, it contains proportionally more product for a larger store than for a smaller store. For convenience in computational testing we approximate the disproportionate nature of flows with an analytic expression giving the flow f_j to the j^{th} of n destinations as

$$f_j = (u - l)e^{-12.8j/n} + l,$$

where u is the maximum flow, and l is the minimum flow. The flows that result from our choice of parameters are representative of data from several crossdocks from which we have data. (As we shall see, our results are robust with respect to the exact form of the distribution of flows.)

We define the *flow cost* of a crossdock to be the total distance between inbound and outbound trailers weighted by the corresponding intensity of freight flow:

$$\sum_{i \in I} \sum_{j \in J} f_j d_{ij},$$

where I and J are the sets of receiving and shipping doors, respectively, and f_j is the flow (in pounds) to the destination at door j. We take flow cost to be an approximation of the

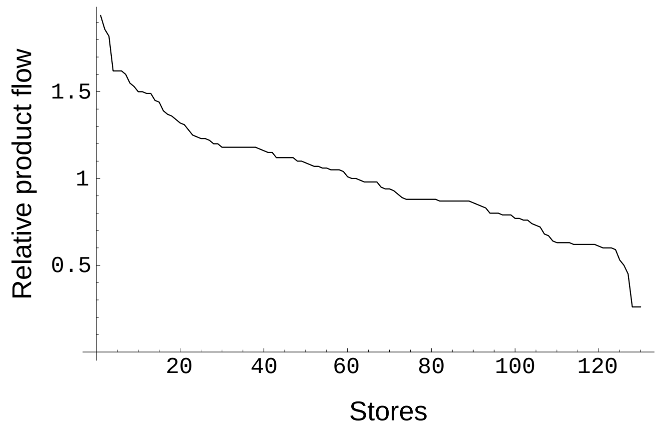


Figure 4: The distribution of flows to stores through a major retail crossdock.

total travel cost across the dock (and therefore an estimate of the variable labor cost to move freight through the facility).

4.1 Layouts

In order to compute the flow cost of a crossdock, we must know at which doors the particular trailers are parked. Elsewhere we have referred to this as the "layout" of the dock; and choosing the best layout is itself a difficult combinatorial problem (Bartholdi and Gue, 2000).

We evaluate the flow cost of a crossdock with good (but suboptimal) layouts produced by two simple heuristics. These heuristics have the advantage of being easy to compute, which was essential to examine the number of configurations we consider. A more important reason for using these heuristics is that the layouts they produce are representative of layouts of actual crossdocks. Both heuristics attempt to concentrate activity among the best doors of the dock.

The Block Heuristic ranks doors according to their average distances to all other doors and outbound trailers by the intensities of freight flows to them, then it greedily assigns the inbound trailers to the best doors and the busiest outbound trailers, successively, to the rest.

We call this a "block layout" because, on an I-shaped dock, the heuristic assigns blocks of inbound trailers to doors on both sides of the middle of the dock and outbound

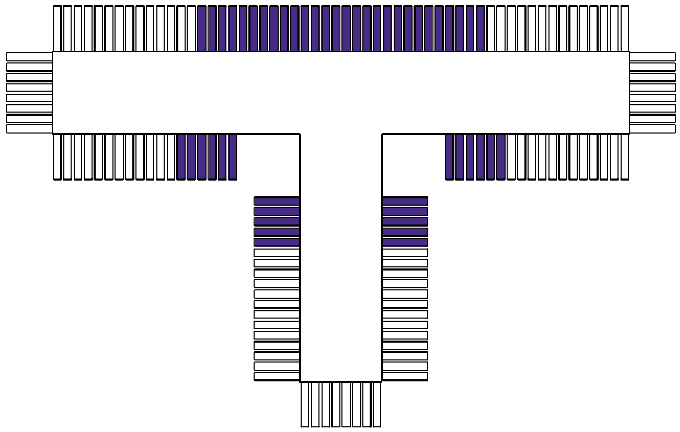


Figure 5: Results of the Block Heuristic applied to the T-shape. Shaded rectangles represent incoming trailers.

trailers to doors on the ends.

We include this heuristic because the resulting layouts are similar to many found in practice. The block structure is appealing to crossdock managers because it logically places trailers with high activity (inbound trailers) in the best doors on the dock. Managers have also told us that such a layout makes supervision easier. Moreover, a block layout can be a requirement for some types of crossdocks. For example, Roadway Express operates a crossdock that receives all trailers in the center of the dock because of an installed conveyor system that handles cartons. (Workers still transport heavy and oddly shaped items with palletjacks and forklifts.)

The Alternating Heuristic ranks doors as before and then alternately assigns an inbound trailer and the next highest-flow outbound trailer to successive doors until all trailers have been assigned.

On an I-shape, this heuristic forms two blocks of inbound trailers, offset on either side of the crossdock, such that opposite each inbound trailer is an outbound trailer. Figures 5 and 6 illustrate results of the Block and Alternating Heuristics on a T-shape.

The Alternating Heuristic produces solutions that are typically 10% better than those of the Block Heuristic, and generally within 10–15% of locally optimal solutions produced by simulated annealing (Bartholdi and Gue, 2000).

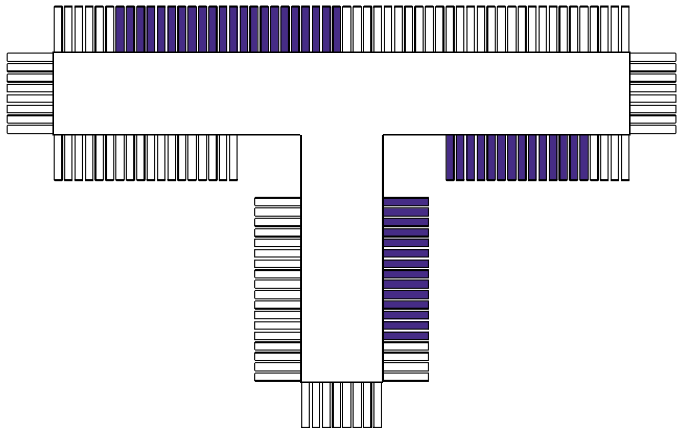


Figure 6: Results of the Alternating Heuristic applied to the T-shape. Shaded rectangles represent incoming trailers.

5 Experiments

We ran a series of computational experiments to determine which shapes have the lowest flow cost and the least traffic congestion. We constructed a variety of crossdocks (in software). For each design we generated a set of trailers representing either uniform or weighted flows, assigned the trailers to doors by either the Block or Alternating Heuristic, and then measured the flow cost of the dock.

We were particularly interested in the relative performances of different shapes over a range from 40 to 400 doors, because this range covers most of the crossdocks in industry. We grew the dock uniformly at every end. For example, to grow a T-shaped dock, we began with a dock having equal pier lengths and then extended all three piers by 2 doors (one on each side) simultaneously. To grow an H, we extended each of 4 piers by two doors simultaneously.

We also studied the relative performances of the several shapes when the fraction of doors that are devoted to receiving varies between 0.05 and 0.50, which includes all crossdocks known to us.

5.1 How wide the H?

Performance of an H-shape depends directly on the length of the center segment, or crossbar. Our experiments indicated that the H is best when the center segment is as small as possible.

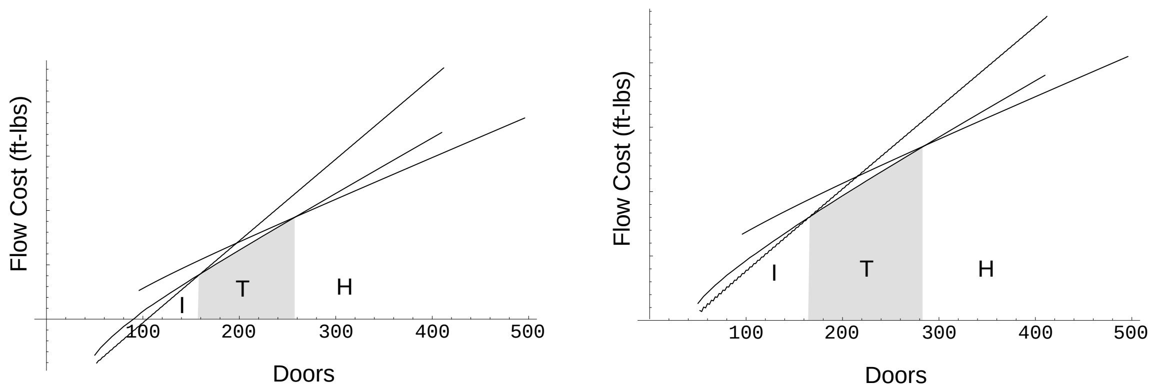
How small can it be? The answer depends on many things, including the length of the trailers it must accommodate, the skill of drivers, whether drivers will be using a standard road tractor or a special yard tractor called a *hostler*, and, for 48 and 53-foot trailers, the placement of the rear axle (which determines pivot points and therefore the turning radius).

One engineer reported that if the crossdock hosts exclusively 28-foot trailers, there need be only about 100 feet between piers. For 48 and 53-foot trailers he estimated the distance to be about 180 feet (Hein, 2001). For our experiments, we assumed conservatively 8 trailers in the center segment, in addition to the lost doors due to inside corners, resulting in a distance of 264 feet between piers.

Adding doors to the center segment violates our rule for centrality because adding 2 doors to the center increases the diameter by 1 door offset (for centrality $2/1 = 2$, rather than centrality 4 as in Table 1). In fact, an H with an extremely long center segment looks like an I.

5.2 Flow cost

The following results were generated by the Alternating Heuristic. Figure 7(a) shows material flow costs for the I, T, and H-shapes when half of all doors are receiving doors and flows to destinations are uniform. (Curves for the L and X-shapes lie above this frontier.) For small docks, the I is superior because it has the best best-doors and its worst doors are not too far from the center of activity, and therefore are not "too bad". As the dock gets larger than 160 doors, the worst doors move far from center. At this point the T becomes attractive because its worst doors (those furthest from the center of activity) are more conveniently located than the worst doors in an I-shape of the same size. (Notice that for very small docks, around 50 doors, the cost for the T is close to that for the I. This is a degenerate condition in which the T has the majority of its doors on the tips of its piers, and most of the travel distance is the result of crossing the dock rather than traversing its length.) The H-shape is poor for small docks because so many of the best door positions are lost to inside corners. But for docks with more than 195 doors the H-shape is better than the I; and for docks larger than about 260 doors, the H is better than all other shapes.



(a) Uniform flows case. (b) Weighted flows case.

Figure 7: Expected costs for the I, T, and H-shapes when half of all doors are receiving doors. The I, T, and H dominate all other shapes for both cases; breakpoints are further to the right for the weighted flows case.

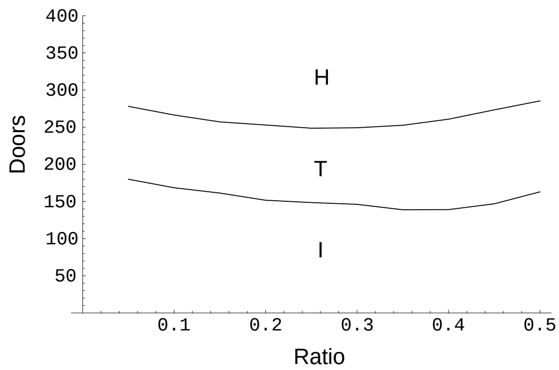
The relative order of preference — first I then T and then H — held for all combinations of characteristics.

Observation 3 *As size increases, the best shapes for a crossdock are I, T, and H, successively.*

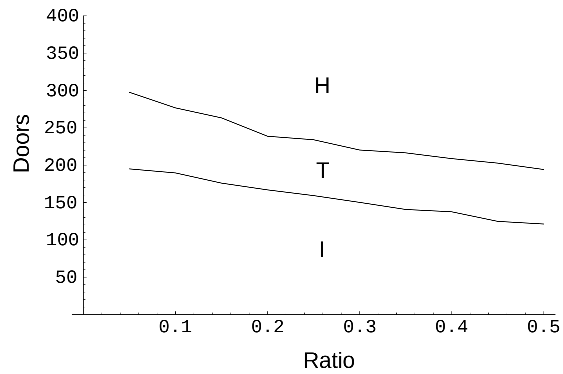
The results are similar for weighted flows, except shifted slightly to the right, so that alternative shapes do not become preferable until later (see Figure 7(b)). This is because weighted flows in effect make the dock smaller: That is, more activity can be concentrated into less area and so the fixed cost of a corner is more significant. The result is that shapes with more inside corners perform poorly until the dock gets very large; or,

Observation 4 *The more concentrated the flow of freight among outbound trailers, the larger the dock must be for more complicated designs to be attractive.*

Figure 8 shows how the breakpoints at which the design should change depends on the fraction of doors devoted to receiving. (In these particular plots the flows are weighted; the results are similar for uniform flows but, again, the breakpoints occur sooner.) The general conclusion remains the same — I is best for small docks, T for larger, H for larger still —



(a) Alternating layout case.



(b) Block layout case.

Figure 8: The effects of the ratio of receiving doors to all doors on the best shapes. The I, T, and H labels indicate regions for which each of those shapes is best.

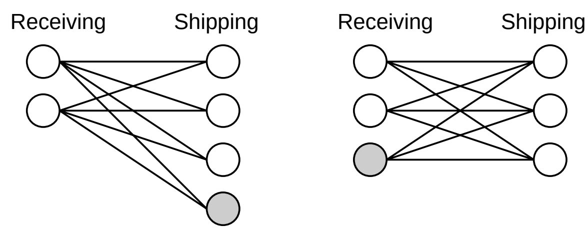


Figure 9: A representation of material flows when the number of receiving doors changes. When the shaded door changes to a receiving door, it becomes more connected, as do the remaining shipping doors; receiving doors are less connected.

but the breakpoints depend on the fraction of doors devoted to receiving. Interestingly, for the block layout the X and H shapes have almost identical flow costs. We believe this is because all the receiving doors are in the center of the dock for both shapes, and both have the same value of centrality.

To gain insight into why the breakpoints vary with the number of receiving doors, consider the bipartite graphs in Figure 9. When receiving doors comprise 1/3 of all doors, the shaded door is less "connected" than when receiving doors comprise 1/2 of all doors; that is, its location relative to other doors is less important. At the same time, the other receiving doors are more connected in the 1/3 case, and the shipping doors are less connected. Because distances among doors differ with dock shape, changing the connectivity in the material flow graph affects the costs of the shapes differently.

Observation 5 *The sizes at which T becomes better than I, and H better than T, depend both on the number of receiving doors and on the layout.*

5.3 Traffic congestion

One problem with very large docks is that they unavoidably generate travel from one end to the other (along the dock rather than across it). Furthermore this along-the-dock travel increases quadratically with the size of the dock. Such travel is costly in at least two ways.

- It is time-consuming; and
- It contributes to traffic congestion and so slows the movement of freight (see the forklift interference model in Bartholdi and Gue, 2000).

To determine how the shape of a crossdock affects congestion levels we recorded the material flow past each door for different shapes having the same number of doors.

To compute the flow past a door we determined a consistent routing of freight between doors and applied it to all inbound-outbound trailer combinations. Figure 10 illustrates the material flow levels past each door on I- and T-shapes having 152 doors, 1/3 doors as receiving doors, and uniform flows. The T-shape has more, but lower, peak flow areas. The peak flow level on the T-shape is lower than on the I-shape because the flow is split in three directions instead of two. This suggests that a large I-shape should be made wider in the center than an equivalent T-shape or else potentially suffer from higher congestion levels. The tradeoff is that widening the dock would add travel time.

Observation 6 *The most conveniently located doors have the most traffic flow past them, and so are most susceptible to congestion.*

Observation 7 *Crossdock shapes with more centrality have lower peak intensities of traffic flow and so are less susceptible to congestion.*

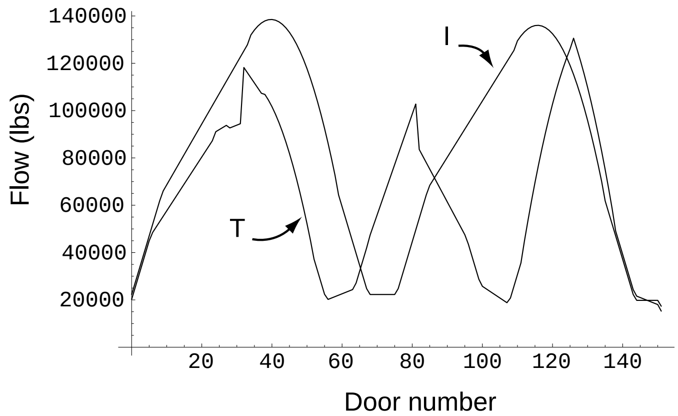


Figure 10: Material flow levels past dock doors for the I and T. Apparent discontinuities are due to the interaction of the alternating layout and the flow around inside corners.

6 Conclusions

To reduce labor costs, the best shape for small to mid-sized crossdocks is a rectangle or I-shape. A rectangle does not lose any doors in the center due to inside corners and so can be more compact than an equivalent L, T, H, or X. The dock should be as narrow as possible, without creating congestion due to insufficient staging area. The cost of a corner suggests that designers should avoid shapes that are topologically equivalent to an I but have more corners, such as L or U.

For larger docks, firms should consider alternative shapes. The T-shape is best for dock sizes between about 150 and 250 doors (the exact breakpoints depend on the pattern of material flows). Even though the T forfeits some of its best door positions to the two inside corners, its worst doors are closer to the center of the dock than for the I-shape and this reduces total travel. It is true that there are many I-shaped docks in this size range but we believe this to be a bad design choice.

For docks in excess of about 250 doors, the H-shape is best. Despite having four inside corners near the center of the dock, the H has the lowest expected material handling costs because its worst doors are not far from the center. The worst doors in an I or T are too far from other doors to make these shapes competitive.

When freight flows are concentrated among few destinations the point will be deferred at which a more complicated design (T, H) becomes attractive. This is because the labor will be concentrated on a subset of the dock and so the dock is, in effect, a smaller dock. Our results also show that the point at which a more complicated shape becomes preferrable depends both on the layout and the fraction of doors devoted to receiving (see Figure 8).

We also observed that shapes with more pier segments, such as T and H, generally have lower peak flow levels, and therefore are less prone to congestion.

Our results also suggest a natural strategy for expanding existing crossdocks: When an I-shape approaches about 150 doors, it should be expanded with a segment in the center, creating a T of about 200 doors. Should the dock grow again, the T should be made an H. Of course, exact points for transition depend on the material flows.

Finally, it is worth remarking that there are some very oddly shaped crossdocks that we have not considered: The Viking Freight System dock in Phoenix forms an obtuse angle, like a dogleg left; the Viking terminal in Seattle is a near-perfect square; and a terminal in Chicago is shaped like an E. As might be expected, these shapes are artifacts of history rather than design.

Acknowledgements

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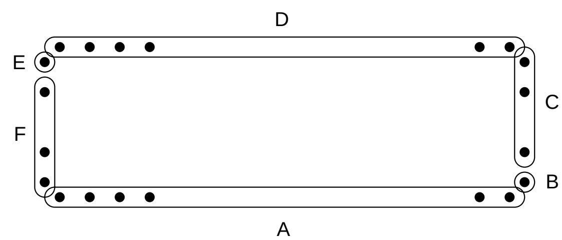
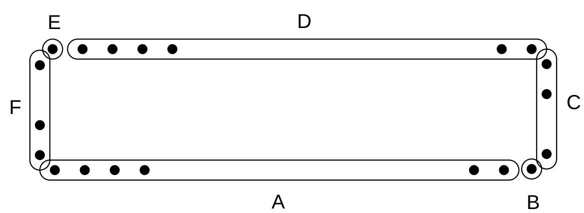
A Proof of Observation 1

Observation 1 *For the same number of doors a narrower dock realizes a smaller average distance between doors.*

Proof Consider a dock of length l and width w, such that $l \geq w$ and $w \geq 2$ (otherwise the dock is as narrow as possible), and a narrower dock having dimensions $l+1$ and $w-1$, as in the figure. Note that there are l doors in regions A and D and $w-1$ doors in regions





C and F. Doors (or, more precisely, door centers) in regions A and F do not move between the two docks; doors regions D and C move one unit to the right and one unit down; doors in regions B and E move one-half unit to the right and one-half unit down. To determine the difference in average distance Δd between doors for the two docks, consider each pair of regions: Doors in regions A and B are the same distance apart, so there is no change in distance. Doors in region C are also the same distance away from those in region A, so there is no change in distance. For doors in regions A and D there is a change: For any door in region A of the top figure, doors in region D above and to the right of that door are the same distance away in the bottom figure (having moved a unit closer and one unit further away); doors to the left of that door are 2 units closer. The rightmost door in region A has $l-1$ doors to the left, the next door has $l-2$, and so on, therefore the change in distance $\Delta d = -2((l-1)+(l-2)+\ldots+1+0) = -l(l-1)$. Similarly, we get

Regions	Δd	Regions	Δd
A $\rightarrow$ B	0	B $\rightarrow$ F	$w-1$
A $\rightarrow$ C	0	C $\rightarrow$ D	0
A $\rightarrow$ D	$-l(l-1)$	C $\rightarrow$ E	$w-1$
A $\rightarrow$ E	0	C $\rightarrow$ F	$(w-1)(w-2)$
A $\rightarrow$ F	0	D $\rightarrow$ E	0
B $\rightarrow$ C	0	D $\rightarrow$ F	0
B $\rightarrow$ D	$-l$	E $\rightarrow$ F	0
B $\rightarrow$ E	0		

Accounting for flow in opposite directions, the change in total distance between doors is $2(w^2 - (l^2 + l + w)) < 0$, so the average distance between doors for the narrow dock is less.

$\square$